Design and optimization of an Er-doped Al_2O_3 adiabatic waveguide taper for double layer integration with Si_3N_4 platform

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The integration of active-passive material platforms is needed to increase the number of optical components on-chip, i.e. achieve more functionalities on PICs. Adiabatic waveguide tapers are of great interest for applications that require short and low-loss transitions between different material platforms. In this work, an Er-doped Al_2O_3 adiabatic waveguide taper is designed for the integration with the standard asymmetric double stripe (ADS) Si_3N_4 TriPleX technology. The tolerance of the taper design to fabrication variations is studied in the wavelength range of 980 nm – 1630 nm. The simulated total loss of the final taper design is ≤ 0.1 dB per coupler.

Introduction

The integration of active-passive material platforms allows for more functionalities on Photonic Integrated Circuits (PICs). There are two main schemes for material integration, namely hybrid and monolithic integration. The monolithic integration scheme allows the incorporation of all the optoelectronic components on a single chip which results in compact devices and cost reductions [1]. For commercial applications, the transitions between the different material platforms should be compact and with low optical losses. One of the common techniques to achieve high-performance coupling between two waveguides is using adiabatic transitions [2]. In an adiabatic transition, the change from one waveguide to another should be smooth and gradual, e.g. by using a tapered section. With the slow variation of the geometry, the mode from the first waveguide evolves adiabatically (i.e. with negligible power losses) to the mode of the second waveguide.

Device design

A 3D schematic of the double-layer integration of Er^{3+}:Al_2O_3 and Si_3N_4 is shown in Fig. 1(a). The Er^{3+}:Al_2O_3 channel waveguides are separated by a thin SiO_2 layer from standard asymmetric double stripe (ADS) Si_3N_4 TriPleX waveguides [3]. The thickness of the SiO_2 spacer is controlled by a chemical-mechanical polishing (CMP) step that is used to achieve a good surface uniformity. Typical thickness values are in the range of 200-300 nm. However, the spacer thickness can be further reduced down to 100 nm by locally etching in buffered HF.

Fig. 1(b-c) shows the cross-section (CS) schematic of the structure with the corresponding electric field intensity distribution of the fundamental TE mode at four distinct positions along the adiabatic coupler. The cross-sections are shown at the ADS Si_3N_4 waveguide core [CS (i)], the ADS Si_3N_4 waveguide core and tip of the Er^{3+}:Al_2O_3 lateral taper [CS (ii)], the tip of the ADS Si_3N_4 lateral taper and the Er^{3+}:Al_2O_3 waveguide core [CS (iii)], and the Er^{3+}:Al_2O_3 waveguide core [CS (iv)]. The fundamental TE mode at the beginning/end of the coupler, i.e. CS (ii) or CS (iii), has a slightly different effective refractive index from the mode at the Si_3N_4 waveguide [CS (i)] or Er^{3+}:Al_2O_3 waveguide [CS (iv)]. The change in effective refractive index produces a mode mismatch loss, visible in their electric field intensity distribution. Then, the mode continues propagating in the tapered region, where the power of the mode is transferred adiabatically from one waveguide to the other. Therefore, the total loss of the coupler is the sum of the mode mismatch losses and the losses occurring in the tapered region.

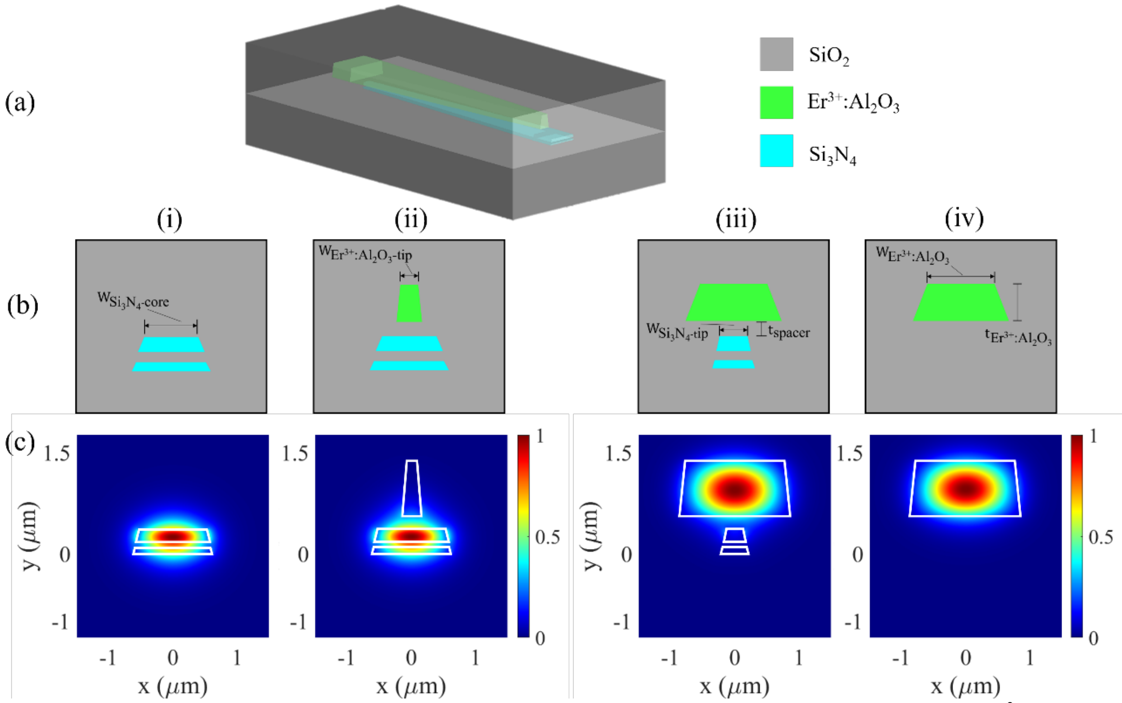

Fig 1. (a) 3D schematic of the coupling region for the double-layer integration of Si_3N_4 and Er^{3+}: Al_2O_3. (b) Schematic cross-sections at (i) the Si_3N_4 core, (ii) the Si_3N_4 core and tip of the Er^{3+}: Al_2O_3 taper, (iii) the tip of the Si_3N_4 taper and the Er^{3+}: Al_2O_3 core, (iv) the Er^{3+}: Al_2O_3 core. (c) E-field intensity of the fundamental TE mode at the respective cross-sections.

Simulation results

Simulations using Lumerical Mode Solutions software were performed to study the performance of the optical couplers considering fabrication tolerances. The methodology combines the Finite Difference Eigenmode (FDE) solver, for the mode field calculations and extracting the mode mismatch losses, and the EigenMode Expansion (EME) solver to calculate the losses in the tapered region.

For the design, the standard width of 1.1 μm was used for the Si_3N_4 waveguide core. The Si_3N_4 width is tapered laterally down to 300 nm with a taper angle of ~0.039° (i.e. taper length of 800 μm) based on previous work [4]. The minimum Si_3N_4 width is limited by the resolution of the stepper lithography process. For the Er^{3+}:Al_2O_3 channel waveguide, a thickness of 800 nm was chosen for its application in waveguide amplifies since it will allow for a high overlap (~80%) between the fundamental TE mode of the signal wavelength and gain material resulting in higher gain. The Er^{3+}:Al_2O_3 core width of 1.6 μm is tapered laterally down to 150 nm, with the same taper length as Si_3N_4, resulting in a taper angle of ~0.057°. The taper width was chosen based on the current achievable dimensions using Electron Beam Lithography (EBL, Raith EBPG5150).

Five wavelengths are considered in the simulations: 980 nm and 1480 nm (i.e., pumping wavelengths for Er^{3+}); 1532 nm, 1550 nm and 1630 nm (i.e., Er^{3+} emission band). The refractive indices for the materials are extracted from experimental measurements (Woollam M-2000UI ellipsometer) and are summarized in Table 1. The simulation analysis focuses on the influence of the EBL process in lateral misalignment (Δx) between

Si_3N_4 and Er^{3+}:Al_2O_3, the taper width variation of the Er^{3+}:Al_2O_3 waveguide, and the thickness variation in the SiO_2 spacer dependent on the CMP process.

Table 1. List of refractive indices used in the simulations.

Material	λ = 980 nm	λ = 1480 nm - 1630 nm
Er^{3+}:Al_2O_3	1.726	1.720 ± 0.001
Si_3N_4	1.993	1.983 ± 0.001
SiO_2	1.455	1.452 ± 0.001

In Fig. 2a the mode mismatch loss as a function of misalignment and SiO_2 spacer thickness of the fundamental TE mode for case 1, i.e. comparison between [CS (i)] and [CS (ii)], and case 2, i.e. comparison between [CS (iii)] and [CS (iv)]. It is observed that the loss is below 0.06 dB for all the simulated wavelengths, misalignments and SiO_2 spacer thicknesses. For case 1, the fundamental TE mode at 980 nm is highly confined to the Si_3N_4 core and therefore the mode mismatch is lower compared to the longer wavelengths. It is observed that when the misalignment increases, the mode mismatch losses decrease. This is because the Er^{3+}:Al_2O_3 taper tip has less influence in the effective refractive index change. A similar trend is observed for case 2, although with a 100 nm SiO_2 spacer the mode mismatch at 980 nm wavelength and shorter misalignments is higher compared to the longer wavelengths. In this case, the Si_3N_4 tip is closer to the Er^{3+}:Al_2O_3 and it induces a relatively bigger change in the effective refractive index compared to the longer wavelengths. In Fig. 2b the mode mismatch loss, for case 1, as a function of misalignment and Er^{3+}:Al_2O_3 taper tip width variation is shown. For these simulations, a SiO_2 spacer of 200 nm was considered. A similar trend as described above is observed. As expected, for wider Er^{3+}:Al_2O_3 taper tip widths, the change in effective refractive index is higher and therefore the mode mismatch loss is also higher. However, for all the taper tip width variations, the mode mismatch loss was below 0.1 dB.

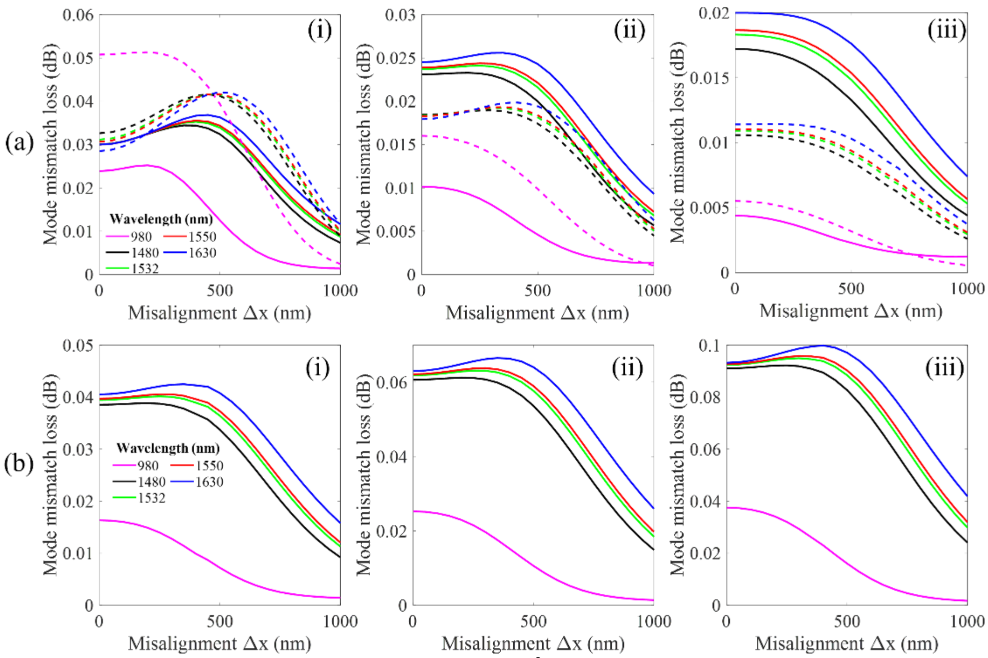

Fig 2. Mode mismatch losses for (a) A 150 nm wide Er^{3+}:Al_2O_3 tip with SiO_2 spacer thickness of (i) 100 nm, (ii) 200 nm, and (iii) 300 nm. Solid lines are for case 1 and dashed lines for case 2. (b) A 200 nm thick SiO_2 spacer and Er^{3+}:Al_2O_3 tip width of (i) 200 nm, (ii) 250 nm, and (iii) 300 nm.

The loss in the tapered region as a function of misalignment is presented in Fig. 3a. It is observed that for both considered Er^{3+}:Al_2O_3 taper tip widths (150 nm and 300 nm) the loss is below 0.03 dB for the for the wavelength range of 1480 nm – 1630 nm. For 980 nm wavelength, the loss increases up to 1.8 dB for misalignment > 800 nm. The total coupler loss, i.e. mode mismatch loss and the loss in the tapered region, is displayed in Fig. 3b. For the considered misalignments and taper widths, the total coupler loss is ≤ 0.1 dB for the wavelength range of 980 nm -1630 nm.

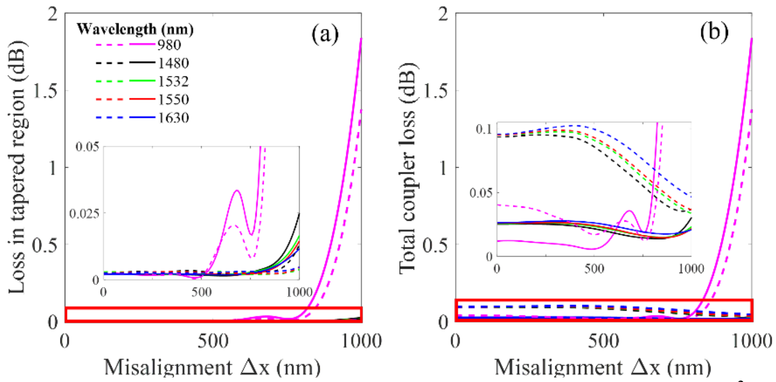

Fig 3. (a) Loss in 800 μm long tapered region and (b) Total coupler losses for an Er^{3+}:Al_2O_3 tip width of 150 nm (solid lines) and 300 nm (dashed lines). A SiO_2 spacer thickness 200 nm was considered. Inset correspond to the section of the red boxes.

Conclusion

In conclusion, an adiabatic optical coupler design for the integration of Er^{3+}:Al_2O_3 in the commercial Si_3N_4 TriPleX platform has been presented. The simulations show a low-loss (≤ 0.1 dB) over a broad wavelength range (980 nm – 1630 nm) for an 800 μm long taper section. The design high fabrication tolerances such as misalignment during the EBL process, Er^{3+}:Al_2O_3 taper tip width variations, and thickness variations in the SiO_2 spacer. The taper length could be further reduced by using different taper shapes by applying numerical methods as shown in [5].

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